The Coordinated Voltage Control Meets Imperfect Communication System

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***Abstract*—High penetration of Distributed Generations (DGs) will have impact on the development of power systems. Due to the uncertainty of the DG output, it becomes extremely difficult to control the system voltage profile. This paper proposes a coordinated decentralized voltage control method, together with a self-excited inverter, that can control the voltage level by reactive power injection/absorption. The time-delay introduced by communications among DGs is considered to validate the proposed control approach. Simulation results show that the coodinated control approach is sensitive to the time-delay in a 33-bus medium-voltage distribution network (MVDN).**

***Index Terms*—distributed generation, voltage control, coordinated decentralized control, time-delay analysis.**

I. Introduction

THE increasing carbon dioxide emissions, the growing world population, the decreasing fossil fuels and rising energy demands contribute to a large renewable energy penetration. According to the U.S. Department of Energy report, the energy demand in the U.S. has increased by 2.5% every year over the past 15 years [1]. Current hierarchical power system will be unable to satisfy such demand. The increasing use of DGs is a promising solution. However, it will degrade the dynamic network performance [2], thus requiring innovative smart grid technologies, such as demand side management techniques [3], [4] and new smart grid communication system designs [5]–[7]. The unpredictable output of renewable energy sources can cause a series of technical challenges. One of the main challenges is voltage fluctuation that needs an appropriate control method to stabilise the voltage.

The voltage regulation approaches can be divided into two categories: centralized control strategies and decentralized control strategies. In the past few decades, the traditional voltage regulation has been mainly implemented by operating On-Load Tap Changer (OLTC), Step Voltage Regulator (SVR) and Static Var Compensator (SVC). In centralized control approaches, the control center can gather all system information and send to DGs to control the reactive power output [8]. Centralized control approach can cause a series of issues due to large communication time-delay between inverters and control centres [9]. For example, N. Takahashi *et al.* [10] proposed a centralized voltage control method to optimize the voltage fluctuation. However, the communication time-delay between control center and DG node was not studied which may cause the voltage out of control in a practical system. To mitigate the effect of time-delay, decentralized control approaches were studied to optimize the Distribution Network (DN) voltage level with DGs and also to provide ancillary services. In [11], a decentralized control method that considers the control priority was proposed to save the reactive power output by adjusting the power factor for a PV system. Using this control approach, each DG is independent from the others, thus without any cooperation and cannot deal with some special circumstances, e.g., DG out of service, greater demand load than usual or larger active power output. If one DG is out of service, the other DGs will not help to improve the voltage level. An autonomous decentralized control strategy was studied in [12] by employing a multi-agent system. However, they did not consider the effect of time-delay in this coordinated control system.

Using coordinated voltage control methods, both inverter control and traditional voltage control approaches can be applied to control the voltage. When one DG is out of service, the other DGs or SVCs can receive this signal and then compensate the reactive power to regulate the voltage level. In this paper, we will study the cooperation among DGs and the time-delay effect will be analysed. Against the literature, new contributions of this paper are summarised as below:

- Given the little literature in the research of analysing communication time-delay in smart grid so far, this paper links an imperfect communication system to a coordinated voltage control problem.
- The time-delay analysis is presented to show the impact of communication time-delay to a coordinated voltage control strategy.
- Simulation results show that, with time-delay, existing approaches cannot control the voltage level as expected and thus may affect the system stability. The existing control method should be modified to adapt to the time-delay introduced by communication systems.

The rest of this paper is organised as follows. The time-delay among DGs is introduced in Section II, and Section III describes the coordinated decentralized control algorithm. Simulation results are presented in Section IV. Section V draws conclusions and discusses future work.

II. Time-Delay among DGs

The uncertainty of renewable energy output and changing demand can affect the voltage value in a very short period of

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time. Accordingly, the control strategy should be implemented in real time. The control speed should be the sooner the better. Therefore, an effective and fast communication technology is crucial to improving the control speed by decreasing its time-delay.

There are several kinds of communication technologies that can be chosen for enabling smart grid communications. The existing cellular networks can be a good option. The 3rd Generation (3G) network can be considered as the backbone of a smart grid communication solution [13]. It has many advantages, such as mature technology, already deployed base stations, a wide coverage, low investment, and large capacity.

Using a coordinated control approach, the time-delay (including communication system delay and decision-making delay) among DGs or controllers could affect the effectiveness of the control algorithm. Without any time-delays, conventional control strategy can effectively regulate the voltage level within the operating range. However, with time-delay, it becomes challenging to control the voltage level. The following paragraphs describe a system model considering both time-delay and voltage control.

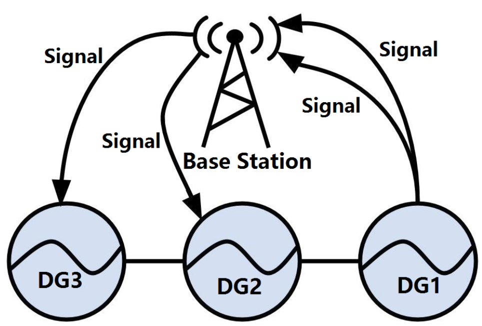

Fig. 1. Exchange of control signals in a communication system.

Fig. 1 shows a basic communication system. First of all, if DG1 node's voltage level is measured and over the operating range, the reactive power injection/absorption value will be calculated by using sensitivity coefficients [14]. Then the reactive power compensation signal will be sent to base station (BS), which could then forward it to selected Most Influence Generators (MIGs), such as DG2 and DG3. Once the MIGs receive the control adjustments signal, they will modify the power factor to control the reactive power. Meanwhile, the MIGs will also acknowledge DG1 to make sure that the control signal is received and operated.

According to the 3rd Generation Partnership Project (3GPP) Release 9, the time-delay can be analysed as follows [15].

1) Choose a scenario (Indoor, Micro cellular, Base coverage urban or High speed), determine the network structure and other parameters, i.e., the number and location of BSs and DGs.
2) Assign the propagation condition, i.e., line-of-sight (LOS) or non-LOS (NLOS).
3) Compute the path loss for each BS-DG link in the system.
4) Generate other parameters, i.e., delay spread.
5) Calculate the delays τ. Time-delay is drawn randomly from the delay distribution defined in [15], with an exponential delay distribution in DN scenarios as below:

$$\tau^{'}_{i,j} = -\sigma_{i,j} r_{i,j} ln(X_{i,j}) \tag{1}$$

where i and j are the transmitter index and receiver index, respectively. $\sigma_{i,j}$ is the delay spread, $r_{i,j}$ is the delay distribution proportionality factor, $X_{i,j} \sim$ Uni$(0,1)$ and index $i = 1, ..., N, j = 1, ..., M$. With uniform delay distribution, the time delay values $\tau^{'}_{i,j}$ are drawn from the corresponding range.

Equation (1) shows the random time-delay calculation. This equation explains that each time-delay between DGs is different and the time-delay, not a fixed value in each time, can reach a high value. In practice, as measurements can be time stamped, it is convenient to know exact time-delay by comparing this time stamp with the received time of measurement signal.

Note: 3G is an obsolete technology due to the explosive growth in cellular communications in past few years. Now, 4G technology is already on the verge of occupying the market and soon will revolutionize the existing systems [16]. The upcoming 5G will be an appropriate technology with less communication system time-delay. Besides this, there exists decision-making delay. When we consider the power system optimization, the decision-making time-delay may become dominant.

III. Coordinated Decentralized Voltage Control

This section will revisit the independent DG control approach in [17] and then propose a coordinated DG control method. The difference between these two control methods will also be discussed.

A. Reactive Power Capability of DGs

The electronic power converter is connected between DG and bus node. The active/reactive power capability value which is the threshold point in voltage control algorithm has been investigated in [18]. The reactive power capability presents the DG maximum allowable reactive power output at different active power output value.

The maximum reactive power output can be written by

$$Q_c = \sqrt{(I_{c,max} V_g)^2 - P^2}, \tag{2}$$

$$Q_v = \sqrt{(\frac{V_g V_{c,max}}{X_t})^2 - P^2} - \frac{V_g^2}{X_t} \tag{3}$$

where Q_c and Q_v are the maximum reactive power output by the limitation of maximum converter current and limitation of maximum converter voltage, respectively.

For different active power output value, the maximum reactive power output will be different with respect to the converter parameters. Combining (2) and (3), the maximum available reactive power capability can be written by [18]

$$Q = \min{(Q_c, Q_v)}. \tag{4}$$

(2) and (3) parameters are set as X_t=0.3, $V_{g,max}$=1.05 p.u., $V_{g,min}$=1.05 p.u., f_{max}=1.0 p.u. [17]. According to (4), each

value of active power with specific power factor working point has the maximum reactive power output value.

B. Independent DG voltage control

The independent DG voltage control approach is building on the sensitivity analysis [14]. The main calculation of the active/reactive sensitivity coefficients can be given by

$$\begin{aligned} \Delta V_{DG}^{P} &= \Delta P_{DG}/\rho_{P} \\ \Delta V_{DG}^{Q} &= \Delta Q_{DG}/\rho_{Q}, \end{aligned} \tag{5}$$

where ρ_Q and ρ_P are the reactive and active power sensitivity coefficient, respectively. ΔP_{DG}, ΔQ_{DG} are DG active and reactive power variation, respectively. ΔV_{DG}^{Q}, ΔV_{DG}^{P} are output voltage variation due to ΔQ_{DG} and ΔP_{DG}, respectively.

During the control process, the node voltage will be measured first and the approach will take action to regulate the voltage if the voltage level is out of the limited range. The reactive power compensation value will be calculated and compensated based on the sensitivity coefficients and the maximum reactive power capability. In this method, the maximum reactive power output value in each DG can be written as

$$Q_{DG}(k) = \max[Q_{cap}(k), Q_{DG}(k-1) - \Delta V_{DG}(k) \cdot \rho_{Q}] \tag{6}$$

where $Q_{cap}(k)$ is the maximum reactive power output in terms of reactive power capability. Index $k = 1, ..., M$ and M is the number of DGs. $Q_{DG}(k-1) - \Delta V_{DG}(k) \cdot \rho_Q$ is the system required reactive power value for each DG.

When the reactive power demand is over the DG capability, active power curtailment will happen to reduce the voltage level. It is obvious that this approach only considers self node voltage regulation without other DGs cooperation. If one DG is out of service, the voltage of this DG node will be out of control. Therefore, a coordinated control approach is proposed to solve this problem.

C. Proposed coordinated voltage control

A coordinated voltage control approach is proposed to regulate the voltage level in scenarios where independent control method can not work. The Most Influence Generator (MIG) is proposed based on the sensitivity coefficients. If one DG's reactive power is changed, other neighbouring nodes' voltage level also will change. And the most affected neighbouring DG is called MIG. The steps of control method are as follows.

1) Check the node voltage level. If the voltage exceeds the operating range, the control method will take action.
2) The number of MIGs will be chosen based on the DG location and network structure.
3) According to the voltage level and numbers of MIGs, this algorithm will calculate the reactive power compensation value of each MIG and send signal to each MIG to control the voltage.
4) Check the reactive power demand is sufficient to compensate the voltage level. If all DGs' reactive power is insufficient, the active power curtailment will be activated to reduce the voltage level.

The total available amount of reactive power injection/absorption will be shown as

$$Q_{DG}(k) = \max[N \cdot Q_{i,cap}(k), Q_{DG}(k-1) - \Delta V_{DG}(k) \cdot \rho_{Q}] \tag{7}$$

where N is the number of coordinated generators. $Q_{i,cap}(k)$ is the maximum allowable reactive power output in terms of reactive power capability of generator i and MIG.

As seen in (6) and (7), one DG's maximum reactive power output is the total available amount in independent control method. However, the coordinated approach can consider MIGs' reactive power as self-node's available reactive power according to the sensitivity coefficient which enlarges the maximum reactive power compensation value and avoids the occurrence of the active curtailment in advance. Only if the reactive power demand is over the total effective DG capability, the active power curtailment would happen. When active power output reduces, the reactive power also could be increased to reduce the active power curtailment value because the active power curtailment would increase the reactive power capability points. Even if the main node DG is out of service, the MIGs can still regulate the reactive power output to maintain the main node's voltage level.

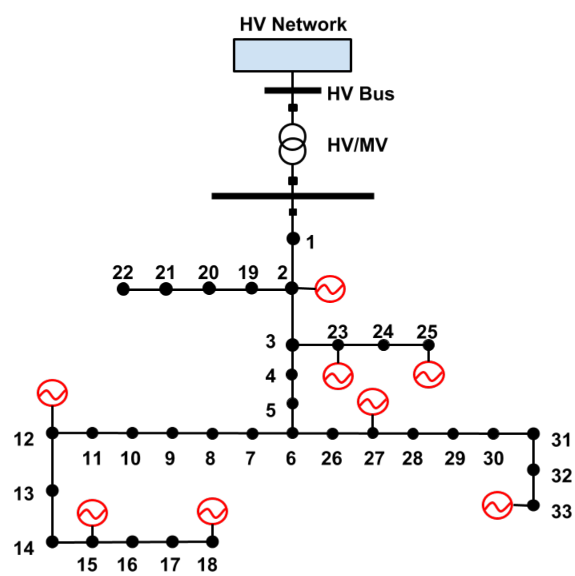

Fig. 2. Radial 33-bus DN under test.

IV. SIMULATION RESULTS

In order to verify the coordinated control approach, a 33-bus MVDN is applied. The single line diagram of the distribution network is shown in Fig.2. This system is 100 KVA, 12.66 KV, radial DN system [19]. It contain 33-bus, 32 branches, four wind DGs(2,12,15,18) and four solar DGs(23,25,27,33). Fig.3 shows the wind and solar generation power profiles of one-day data in the UK in October 2015 from Solax Power Ltd.

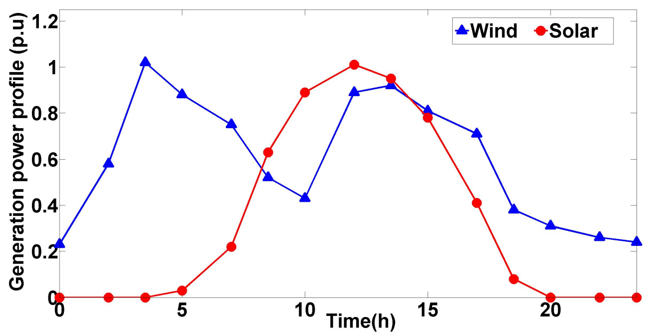

Fig. 3. Generation Power Profile (p.u.).

A. Independent vs Coordinated Methods

Without any control action, the voltage level would exceed the upper limit in peak time in Fig.4 (a) and the maximum voltage value is almost 1.09 p.u.. However, the exceeded voltage level points are regulated into the operating range by the proposed coordinated voltage control strategy as shown in Fig.4 (b).

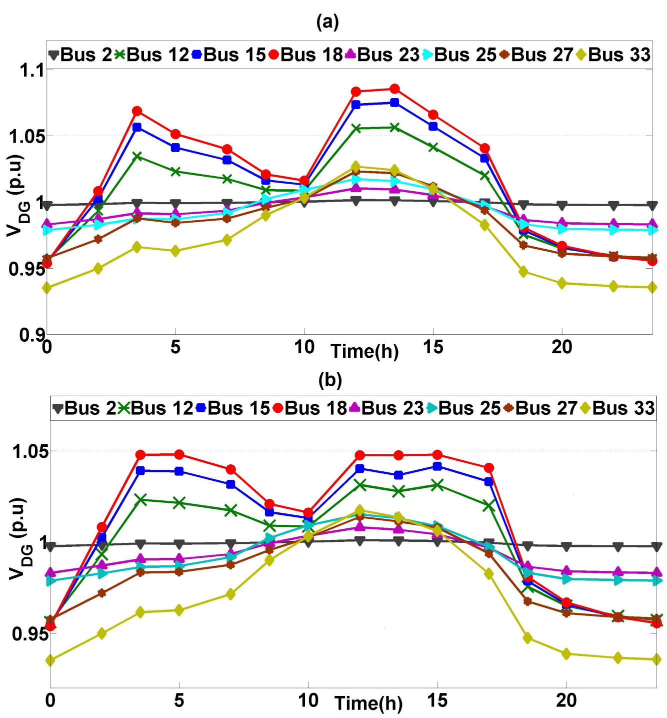

Fig. 4. DGs bus voltage level (a) without control action (b) with coordinated control action.

Compared with independent method, the coordinated approach can adjust all DGs' power factor cooperatively. Table I shows the DGs reactive power injection by two methods. In the independent control method, the reactive power injection 0.45 p.u. in bus 15 is much larger than that in other buses because of the non-cooperation. In general, 0.45 p.u. is almost the maximum allowable reactive power value. If the load of bus 15 increases more, the maximum reactive power compensation will not meet the requirements and the active power curtailment will be activated easily.

The coordinated control strategy can decrease the maximum reactive power from 0.45 p.u. to 0.34 p.u. in Table I. And 0.34 p.u. can greatly reduce the possibility of active power curtailment occurrence even if the load rise to higher value than usual. The higher power factor can also improve the DG performance. In the independent approach, if one DG is out of service, the MIGs will not regulate this DG's voltage level due to non-communication. However, in the coordinated approach, these MIGs can communicate with each other and exchange operating data to maintain the voltage level.

TABLE I
REACTIVE POWER INJECTION BY DIFFERENT APPROACH

	Independent control Maximum output	Coordinated control Maximum output
Bus 12	0.33 $p.u.$	0.34 $p.u.$
Bus 15	0.45 $p.u.$	0.34 $p.u.$
Bus 18	0.18 $p.u.$	0.34 $p.u.$

B. Control with Time-Delay

Although the coordinated control method can control the voltage level without time-delay, the time-delay simulation results show that the voltage level can be out of control. Too large voltage fluctuation will cause the system out of control. In other words, it is necessary to modify this control strategy to maintain the voltage level when the time-delay exists.

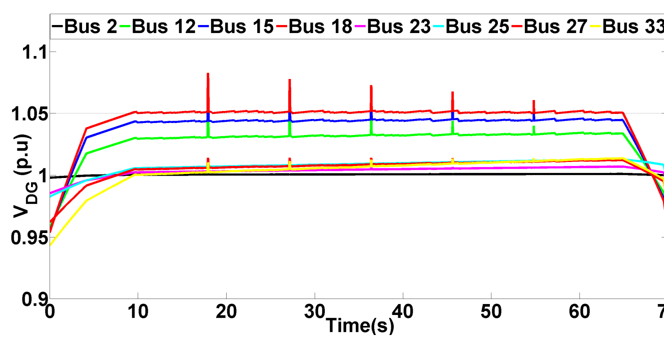

Fig. 5. DGs bus reactive power control when considering the time-delay.

Fig. 5 presents that the voltage level controlled by the coordinated control method is out of control with time-delay. It can be seen obviously that the voltage level during the large demand load or active power output change can not be regulated and would increase into a high value during the time-delay period.

Power system stability could be affected by voltage collapse from a second to tens of minutes and transient voltage fluctuation is often the main concern [20]. According to Fig. 5, the voltage level is over the limited value 1.05 p.u. during most of the control time. The large voltage rise means when the load drop or DG output rise occur suddenly, the voltage level would increase to a high value without any control action due to time-delay. If it happens in real power systems, the system performance and electrical equipments would be damaged. If the voltage drop or rise is too large in few seconds, the power system even can not be restored again.

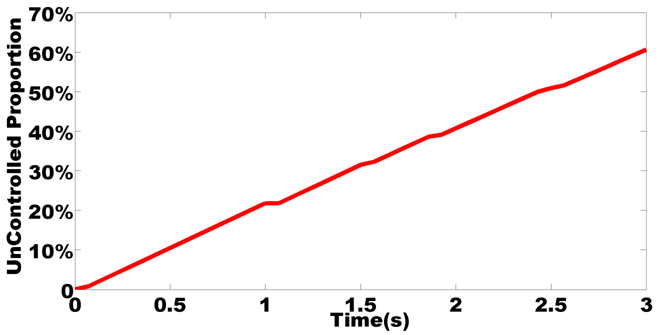

Fig. 6. Probability of voltage out-of-control when the time-delay varies.

Fig. 6 presents that the uncontrolled voltage level proportion compared with the non-time-delay results will increase from 0 to 60% when the time-delay varies from 0 to 3.0s. The larger time-delay, the bigger proportion of out control range. Voltage stability is affected by various components in a wide time range. Therefore, it is necessary to consider the time-delay model and modify the control strategy to maintain the voltage level. The time-delay analysis can improve the control approach to maintain the voltage properly and reduce the incidence of system instability. In the future, a novel control strategy need to be designed to fit the time-delay and different change rate scenario.

V. Conclusion and Future Work

The large number of DGs in MVDN can result in voltage fluctuation issue. Voltage rise can cause loss of partial load and reduce the life span of equipment. The proposed coordinated decentralized voltage control approach regulates the voltage level effectively in the case of no time-delay. The MIG concept could reduce the possibility of active power curtailment occurrence and improve the DG power factor. The reactive power flow reduction in MV network can decrease the power loss [21].

The 33-bus MVDN was used to verify the proposed control method. However, it is unable to maintain the voltage level effectively when considering the time-delay in the DN. Due to its complicated scenario and DG output change rate, it is necessary to revise the control approach in real time and realistic scenario to regulate the voltage. Moreover, the cooperation with traditional reactive power compensators can also be applied into the system to control the voltage that can avoid the active power curtailment. The communication system model in this paper is still imperfect. If the power optimization, e.g., considering economic efficiency, is studied for further research, the system performance analysis with a complete 4G/5G communication time-delay model (also considering decision-making time-delay) will be necessary.

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